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# CTS Load Carriage System Phase III D -Stage 3: Final Design Evaluation using the APLCS Load Carriage Simulator

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## P CTS Load Carriage System Phase III D -Stage 3: Final Design Evaluation using the APLCS Load Carriage Simulator

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## Abstract

The objective of this study was to conduct a standardized assessment of the Clothe the Solder Integrated LCS pack, Final Design (CTS-FD) on a computerized Load Carriage (LC) Simulator. Specifically, the LC Simulator measured variables which assess the load control and load transfer capability of the CTS Integrated LCS pack. These aspects of pack design were comprised of several displacement, force, moment and pressure variables that had been validated on previously tested systems where LC Simulator outputs were compared to assessments by experienced users during human trials. The CTS-FD pack was evaluated without the Clothe the Soldier tactical assault vest (TAV).

The LC Simulator consisted of interchangeable anthropometrically weighted manikins ($50^{th}$ percentile male used) which were covered with a skin-like surface, driven by computer controlled pneumatic activators programmed to elicit a walking displacement pattern of ±25.4 mm amplitude and 1.8 Hz frequency. A trial consisted of measuring inertial properties and dimensions, loading the pack with a 25 kg payload, mounting the pack and balancing the moments. Five intervals of 10 seconds of data were recorded over a 1200 second period. By this approach, the pack was assessed on the initial setup and after a sustained period of walking. Output variables were: three dimensional motions of the pack's centre of gravity relative to the person's motion; forces and moments from a three dimensional load cell at the level of the hips; skin average pressures, peak pressures and skin forces over the anterior and posterior shoulders, and upper and lower back.

To examine the resistance of the pack frame to motions in three planes, a pack stiffness jig was developed. This jig consisted of a two-piece anatomical human trunk model ($50^{th}$ percentile male) which was designed to confine motion to one plane at a time. Using a load cell and multi-turn precision potentiometer, pack resistance to flexion/extension, lateral bending and torsion were evaluated through a set protocol.

The CTS-FD rucksack performance was compared to previously validated variables for load control and load balance from the LC Simulator. Results were expressed in comparison to the mean value, superior decile (best 10%) and inferior decile (worst 10%) values. For load control, the CTS-FD rucksack ranked as superior in: control of relative pack-torso motion, lower average and peak pressures in the anterior and posterior shoulder region, and lower average reaction moments for vertical, medial/lateral and forward reaction moments at the hip.

# 1.0 Scope of Report

## *1.1 Objectives of Test*

The two main areas of interest when investigating load carriage are load control and load transfer. Proper load control is necessary for the user to maintain balance and mobility during load carriage. Relative displacement between user and load carriage system, rotational moments generated during load carriage, and resistance of the LC system to deflections within the range of human motion, are quantitative measures used to define the load control ability of a load carriage system. Capacity for load carriage, muscle fatigue during carriage, and risk of tissue injury are all dependent on load transfer to the user. Measurement of skin contact pressures in significant load bearing areas and forces applied by the load allows for an assessment of the load transfer capability of the LC systems under study.

## *1.2 System Evaluated*

Testing of the CTS-FD rucksack, performed by the Ergonomics Research Group at Queen's University, included measurement of the following variables:

1. Shoulder strap and waist belt tension.
2. Relative displacement between LC system and torso.
3. Hip reaction forces.
4. Hip reaction moments.
5. Skin contact pressures in five regions.
6. Torsional pack stiffness.
7. Lateral pack stiffness.
8. Forward flexion stiffness.

Comparison of the results from previous LC system tests with those of the CTS-FD was also performed, allowing for comparison of design features and evaluation of system strong points. The CTS-FD system was tested without the CTS tactical vest.

# 2.0 Methods

## *2.1 LC Simulator Testing*

### 2.1.1 Torso Specifications and Preparation

A family of four anthropometric manikins ( 5$^{th}$ and 50$^{th}$ percentile females, and 50$^{th}$ and 95$^{th}$ percentile males, as defined by Safework™ anthropometric software) were constructed for LC simulator testing. Each manikin was comprised of a head and trunk section, with arms truncated in the mid-humeral region and legs extending to just below the buttocks.

These human models consisted of a fibreglass outer shell with expandable poured polyurethane foam filling. Proper mass distribution was achieved by thoroughly mixing aggregate with the interior foam. A vertical cylindrical cavity was created in each manikin to allow for mounting of a six degree-of-freedom load cell. In each case, the neutral axis of the load cell was positioned at the approximate location of the manikin's hips. This load cell was further mounted on a single axis articulating vice, which permitted the manikin and LC system to be placed in a balanced anterior body lean position for load carriage. Finally, the surface of each manikin was covered with a 5 mm thickness of Bocklite™, a synthetic skin-like material used on prosthetics, to approximate the compressive response of human skin over bone. For all tests, the manikin was dressed in a Canadian Forces standard issue combat shirt.

### 2.1.2 LC System Loading and Mass Properties

The LC payload was created by locating a concentrated mass at the centre of the system volume. The mass used in the LC system was 25 kg +/- 1 kg and was comprised of rectangular steel plates. These plates were held in position by a rigid polystyrene foam shell which filled the LC volume. Three dimensional location of the LC system centre of gravity is shown in Table 2.1-1 for the pack with payload. Mass of the pack, unloaded and loaded, is also included.

**Table 2.1-1** Mass properties of load carriage system.
Total mass for both the unloaded and the loaded LC system, location of the centre of gravity in three dimensions, and the physical dimensions of the LC system are all included.

| **Load Carriage System : CTS-FD** | | | |
|---|---|---|---|
| **Mass :** | **LC System only** | 4.35 | (kg) |
| | **LC System w/ load** | 28.67 | |
| **Physical Size :** | **Length (k)** | 700 | (mm) |
| Main bag, no side pouches | **Width (j)** | 340 | |
| | **Depth (i)** | 252 | |
| **Centre of Gravity*** : | **Height (k)** | -395 | (mm) |
| | **Width (j)** | 170 | |
| | **Depth (i)** | -150 | |

* - all C of G measurements are relative to the lower left corner of the LCS as it is worn.

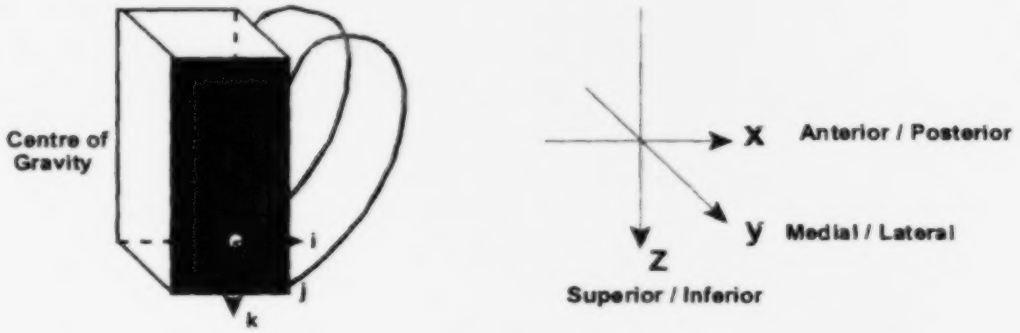



Figure 2.1-1 Orientation of reference axis for displacement and force measures.

### 2.1.3 Test Protocol

The LC Simulator (Figure 2.1-2) consists of the previously described rigid manikin, mounted on a programmable displacement platform. This platform rests on three air cylinders which allow vertical motion as well as rotation about the x (anterior/posterior) and y (medial/lateral) axes. A computer controlled vertical displacement pattern (+/- 25.4 mm amplitude, 1.8 Hz frequency) simulates marching, and linear displacement transducers provide positional information for the control system. Feedback control is accomplished by varying the differential pressure across each cylinder face.

The CTS-FD rucksack was loaded with the payload, positioned on the simulator and properly adjusted. A standard LC Sim test, which is comprised of 1200 seconds of simulated walking, with data recorded at 300 second intervals was performed. The sampling rate for all data collection is 55 Hz and the duration is 10 seconds (minimum). Outcome measures from the LC Sim test consist of; the relative displacement between manikin and the LC system; skin contact pressures on the shoulders, upper back, and lower back; and hip reaction forces and moments. The following sections describe the methodology and instrumentation used to collect LC System characteristic data.

Figure 2.1-2. CTS-FD system (no Tactical Assault Vest) positioned on LC simulator manikin. The manikin has yet to be leaned forward to balanced the hip moment induced by the weight of the rucksack. Final forward lean angle was 11.5°.

### 2.1.4 Strap Forces

During the setup phase of the LC Simulator testing, strap force tension transducers were placed in-line in the right lower shoulder strap and the right half of the waist belt, free of any hip/kidney padding. Attachment of the transducers was accomplished by placing a pin through an attachment ring in the end of the carrier material of each transducer, ensuring that all tension in the strap was transmitted through the transducer. Output from the force transducers was amplified by a Keithley MetraByte DATAQ system (Keithley MetraByte Instruments Incorporated) and recorded digitally as part of the test record. Initial settings of 60 +/- 5 N in the shoulder strap and 50 +/- 5 N in the waist strap were used for all load carriage trials. The force transducers were constructed with four foil style strain gauges, attached in a full Wheatstone bridge configuration to a rounded I-shaped 6061-T6 aluminum carrier with a length of 38.00 mm and thickness of 1.14 mm. Static testing of the transducers showed they were highly linear ($r^2 > 0.9995$) with a small

standard error (<0.01 V)[1].

The upper and lower hip stabilizer straps were preset to 65 N using a Chatillon® pull gauge. These straps are identified as # 3 and # 4 in Figure 2.1-3. The upper hip stabilizer ties the hip belt to the lateral edge of the frame sheet while the lower hip stabilizer is attached to the lower end of the lateral stiffening rod.

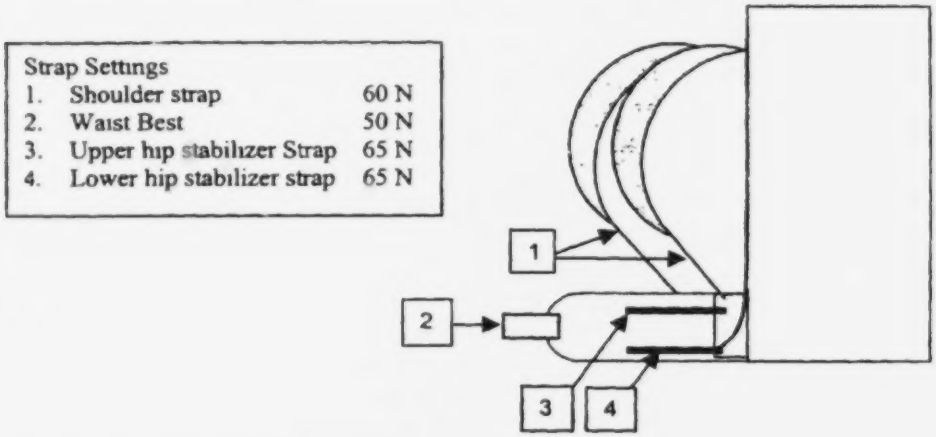



Figure 2.1-3 Location and preset tensions in CTS – FD LCS straps.

### 2.1.5 Relative Displacement of LC System and Torso

An electromagnetic position tracking system (Fastrak™ by Polhemus Incorporated) was used to provide three dimensional displacement data. The source for the Fastrak™ was affixed with nylon screws to the underside of the left arm of the manikin. A Fastrak™ sensor was also attached in a secure position to the superior polystyrene surface of the LC System payload. The resultant location was 305 mm superior and 48 mm posterior to the payload centre of gravity (COG). Displacement data, for the payload with respect to the source, was recorded for 10 seconds at 55 Hz every 300 seconds over the duration of the test. Translation from the superior payload sensor location to the loaded pack centre of gravity was performed to provide estimated displacement vectors between the centre of gravity of the loaded LC system and the manikin.

Direct comparison of Fastrak™ positional data with data collected from an opto-electric positional recording system (Optotrak™ by Northern Digital Incorporated) with high precision (RMS error <0.01 mm) provided an RMS error for Fastrak™ data of 0.65 mm.

[1]Stevenson, JM., Bryant, JT., Reid, SA., Doan, JB., Siu, D., Saunders, G., MacNeil, SK., and C. Barrick . (1996). Validation of the Load Carriage Simulator : Research and Development of an Advanced Personal Load Carriage System. *DCIEM Contract #W7711-4-7225/01-XSE.*

### 2.1.6 Reaction Forces and Moments

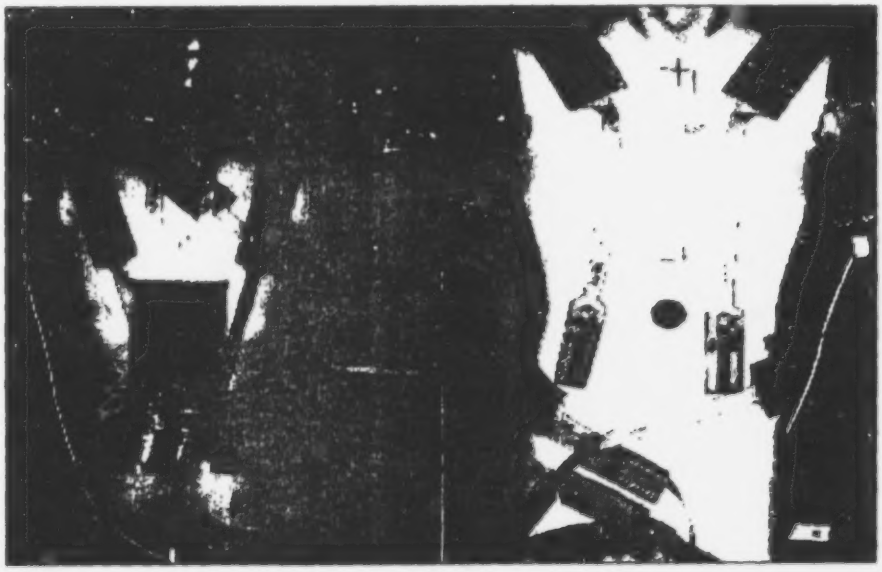
Ground reaction forces and moments were collected using a 6 degree-of-freedom load cell (AMTI Incorporated) based on a body fixed coordinate system located at the hip and oriented along the long axis of the trunk. The outcomes from this instrumentation were reported as a resultant mean force (N), in which reaction forces in the Fx (forward and back), Fy (side to side), and Fz (up and down) directions were combined vectorially. Similarly, a resultant mean moment (Nm) was defined by combining the Mx (lateral), My (flexion/extension), and Mz (torsional) moments.

Two factors affect the moments and forces transmitted through the load cell: motion and mass of the moving bodies. In the LC simulator, the mass of the torso requires a significant reaction under the imposed displacement from the positioning actuators. This is in addition to the reactions needed to move the payload itself. To compensate for these effects, a two-step procedure is used. First, an initial run of the 50$^{th}$ percentile mannequin with no load carriage system in place is used to generate a baseline of reaction moments and forces. These values are then subtracted from the results of a run in which includes the load carriage system. The next step is to normalize the reaction values by dividing them by the total payload of the system. The payload is the sum of the pack load, the weight of the pack itself, the weight of additional load carriage devices (such as webbing or vests), and the weight of clothing. The resultant *normalized* values are expressed as Nm/kg for moments and N/kg for forces. This method of normalization is typical for biomechanical measurements. A normalized force of 9.81 N/kg indicates a force of 9.81 N act for each kilogram of load carried. This is equivalent to the weight of the payload and is sometimes expressed "1 x Payload Weight". A normalized force of 12.2 N/kg, for example, would be expressed as 12.2/9.81 = 1.24 x Payload Weight.

### 2.1.7 Skin Contact Pressures

An F-Scan™ pressure sensor system (Tekscan Incorporated) was used to acquire contact pressure data on the manikin skin over the anterior shoulder, posterior shoulder, scapula and low back region. Figure 2.1-4 shows the orientation of the F-Scan™ 9810 pressure sensors, which were affixed to the manikin with a non-permanent spray adhesive. The F-Scan™ system uses a matrix of force sensitive resistors, which are arranged in a rectangular pattern and contained between two flexible polyester plastic sheets. At full size there are 96 force sensitive resistors, spaced over a region 206 mm by 76 mm. When the thin polymer foil in an element is compressed, the voltage passed across the element changes. This change is sensed by system software, and is recorded as a load normal to the sensor surface, based on individual calibration for each sensor. Information is transferred to the computer through a signal processing unit and cable to a computer card. This information can be replayed in 'movie' format, which can give a dynamic measurement of force, average and peak pressures, active area, or duration of contact. Previous testing at Queen's (DCIEM Contract #W7711-4-7225/01-XSE) has found the F-Scan™ system standard error of the mean to be 9.6 % for average pressures and 14 % for peak pressures. Also, use of the sensors on a curved surface leads to a 9% standard error of the mean for average pressure results[2].

For LC system testing, pressure data were reported in terms of peak dynamic pressures (kPa) and average pressure over all active cells of the sensors (kPa) in the anatomical areas of interest; anterior shoulder, posterior shoulder (scapula), hip, and lower back



[2]MacNeil, SK. (1996). Validation and development of a mathematical model of the shoulder for load carriage Master's Thesis, Queen's University, Kingston, ON. (Unpublished).

Figure 2.1-4. LC Simulator manikin, with F-Scan™ pressure sensors in place.

## *2.2 Stiffness Testing Jig*

### 2.2.1 Torso Specification and Preparation

A pack stiffness test jig was developed to provide a measure of pack stiffness in three degrees of freedom. The load carriage equipment to be tested is placed onto a two-piece anatomical human trunk model (50$^{th}$ percentile male). The model is covered with a layer of compliant synthetic skin, 5mm thick Bocklite. The upper torso portion of the model is free to rotate about a horizontal axis (y-axis for forward bending or x-axis for sideways bending) on two oil impregnated metal powder sintered bearings at the L3/L4 location of the human spine, or about the vertical axis (z-axis for torsional twisting) on a thrust bearing at the L4/L5 location. Only one degree of freedom is active for each type of test, with the other degrees of freedom mechanically locked. The lower portion of the model is vertically fixed to a steel support.

### 2.2.2 Torsional Stiffness

For the torsional twisting tests, load/torque was applied in the form of a horizontal force acting on a moment arm of 0.137m. This was achieved by means of a cable wrapped around a 0.273m diameter pulley on the overhead load transfer assembly (LTA). A modified trailer winch (Fulton Performance Products Incorporated) fitted with a multi-turn precision potentiometer (Bourns Electronics) was used to generate and measure rotation of the upper torso relative to the waist section of the trunk model. A torsion load cell was installed on the drive shaft to measure pack resistance to such rotations. Studies have shown that the average relative angle of twist during walking is approximately 18 degrees, which is ±9 degrees about the neutral axis[3]. A value of 12 degrees from neutral was used as the maximum for testing. Load was applied manually with the winch in a 60 seconds test cycle (25s ramp up, 10s hold, 15s ramp down, and 10s hold) to minimize inertial loads. Testing was repeated three times to ensure reproducibility.

### 2.2.3 Forward and Lateral Bending Stiffness

Load/moment was applied in the form of a horizontal force acting on a moment arm of 0.927m. This was achieved by means of two opposing cables attached to the LTA on a roller track. Each cable was pre-tensioned by a 5 kg mass to maintain proper alignment. An in-line load cell was installed in the cable to measure cable tension fluctuations during each load cycle. A second winch fitted with a potentiometer was used to induce and measure the horizontal

[3]Rose, J., and JG. Gamble. (1994). **Human Walking - 2$^{nd}$ Edition**. (Williams and Wilkins, Baltimore, Maryland, USA.). 263 pp.

displacement of the LTA. Maximum excursion of the LTA was 1.035m resulting in a forward bending angle of 48 degrees. For lateral bending tests, the anatomical trunk model was rotated 90 degrees vertically about the base while keeping the bearing assembly in its original orientation with respect to the LTA. Excursion of the LTA was reduced to a maximum of 0.305m during lateral tests, resulting in a maximum sideways bending angle of 18 degrees. The normal range expected during walking gait is 2-7 degrees[4].

### 2.2.4 Test Protocol

Empty load carriage systems were used in this test to generate baseline LC system stiffness values, without the increased pack stiffness due to kit items. Each pack was placed in position on the manikin and all straps were securely fastened. Using in-line force transducers, the shoulder straps and the hip/waist strap were pre-tensioned to 55 N and 40 N respectively, the same settings were used in the load carriage simulator tests.

During each test run, analog signals from the two load cells and two potentiometers were sampled at 5 Hz over a three minute period using a PC-based data acquisition system. A spreadsheet was used to post-process the data. Only the loading phase of each test cycle was analyzed. Load cell data was filtered first by averaging over one degree intervals of rotation and further averaged over three repeated test runs. For forward and sideways bending tests, the apparatus displayed a resistance against the bending motions. Baseline reference tests were established for the apparatus ( without pack or equipment) and a baseline correction was applied to the data sets by subtraction. For torsional twisting tests, the upper torso response had no discernable effect on the torque transducer output and no baseline correction was required. The information was reduced to bending moments or torque about the hinge in Nm and relative rotation in degrees to produce characteristic moment-rotation curves for each load carriage system configuration. Linear regressions were performed on each LC system data set to obtain an aggregate pack stiffness (slope of a linear regression).

[4]Ibid.

# 3.0 Results

## *3.1 LC Simulator - Displacements and Forces*

### 3.1.1 Strap Forces

The mean tension for the lower right shoulder strap and the right waist belt for one test with the FD - CTS Rucksack, no TAV, system are presented in Table 3.1-1. The full data set for one trial is included in Annex 3.1.

**Table 3.1-1** Shoulder strap and waist belt tension for the FD - CTS Rucksack, no TAV. The mean tension in these two suspension elements, along with the standard deviation, is presented.

| | **Tension** (N) | **SD** (N) |
|---|---|---|
| **Shoulder Strap** | 56 | 18 |
| **Waist Belt** | 53 | 14 |

### 3.1.2 Displacements

The relative displacement data for the LC System is available in Table 3.1-2. Annex 3.1 contains the entire data set for the test trial. Range is defined as the difference between the minimum and maximum displacement, in one axis, measured over a 10 second sampling interval.

**Table 3.1-2** Relative displacement between pack and torso.
Motions in x, y, and z directions were combined vectorially to produce a resultant displacement. Ranges and corresponding standard deviations are indicated.

| | **Range** (mm) | **SD** (mm) |
|---|---|---|
| **X** | 1.32 | 0.36 |
| **Y** | 0.84 | 0.27 |
| **Z** | 0.52 | 0.22 |
| **R** | 1.65 | |

### 3.1.3 Reaction Forces

Table 3.1-3 contains the mean normalized reaction forces, as well as mean total reaction forces and standard deviations in all three axis, for one test trial with the FD - CTS Rucksack, no TAV, system. The full data set is also available in Annex 3.1.

**Table 3.1-3** Reaction forces for LC system testing.
Forces in x, y, and z directions were combined vectorially to produce a resultant force (r). Mean normalized forces, total forces, and standard deviations for one trial are presented.

| | **Normalized Force** (N/kg) | **Force** (N) | **SD** (N) |
|---|---|---|---|
| **X** | 8.7 | 211 | 62 |
| **Y** | 2.8 | 69 | 25 |
| **Z** | 12.0 | 292 | 252 |
| **R** | 15.1 | 366.8 | 260.7 |

Mean and normalized force amplitudes.

| | **Normalized Force Amplitude** (N/kg) | **Force Amplitude** (N) |
|---|---|---|
| **X** | 2.1 | 50.4 |
| **Y** | 0.76 | 18.5 |
| **Z** | 8.04 | 195.3 |
| **R** | 8.3 | 202.5 |

### 3.1.4 Reaction Moments

Table 3.1-4 contains the average normalized reaction moments, in all three axis, for one test trial with the FD - CTS Rucksack, no TAV, system. Total reaction forces and standard deviations are included in the table, and Annex 3.1 contains the full data set for the trial.

**Table 3.1-4** Reaction moments for FD - CTS Rucksack, no TAV testing.
Mean normalized moment, mean reaction moment, and standard deviation are presented in all three dimensions. Resultant moment (r) was the vectorial combination of the axial moments.

| | **Normalized Moment** (N.m/kg) | **Moment** (N.m) | **SD** (N.m) |
|---|---|---|---|
| **X** | 0.5 | 13 | 24 |
| **Y** | 0.1 | 3 | 34 |
| **Z** | -0.03 | -1 | 26 |
| **R** | 0.5 | 13.4 | 49.1 |

Mean and normalized moment amplitudes.

| | **Normalized Moment Amplitude** (N.m/kg) | **Moment Amplitude** (N.m) |
|---|---|---|
| **X** | 0.4 | 12 |
| **Y** | 1.4 | 39.5 |
| **Z** | 0.1 | 4 |
| **R** | 1.5 | 41.5 |

## *3.2 LC Simulator - Pressure Measurements*

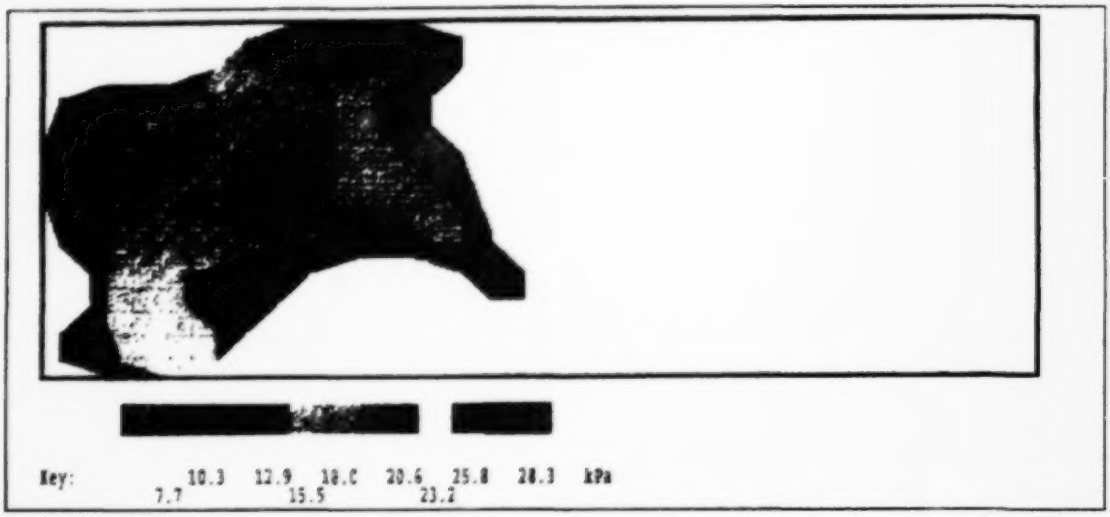
The results of pressure measurements made with the F-Scan™ during the testing of the CTS-FD rucksack, (no TAV), can be found in Table 3.2.. The information presented consists of the average pressure for one recording sample (10 seconds), the peak pressure experienced during this sample, the ratio of peak pressure to average pressure (pressure differential index (PDI)), and the force experienced by the wearer in these areas. The reported time interval is selected based such that all sensors monitored have captured a clean continuous signal and, preferably 900 or 1200 seconds have elapsed to minimize sensor creep response effects.

**Table 3.2-1** Pressure measurement results for the CTS-FD rucksack, no TAV. Average and peak pressure results, along with the peak to average pressure differential ratio (PDI) and the contact force, are included for one sample period during a dynamic LC Sim trial.

| **Anatomical Region** | **Average Pressure** (kPa) | **Peak Pressure** (kPa) | **PDI** | **Force** (N) |
|---|---|---|---|---|
| Axilla & Lateral Pectoral Region | 24.1 | 46.4 | 1.93 | 60.1 |
| **Anterior Shoulder** | 15.4 | 25.8 | 1.67 | 74.8 |
| **Posterior Shoulder** | 6.2 | 7.7 | 1.24 | 4.0 |
| **Upper Lumbar** | (n/a)[1] | (n/a)[1] | (n/a)[1] | (n/a)[1] |
| **Lower Lumbar / Sacrum** | 15.2 | 27.1 | 1.78 | 58.3 |
| **Iliac Crest / Hips** | 14.6 | 30.9 | 2.12 | 17.9 |

1. - no measurable contact pressure in this area for the FD- CTS Rucksack, no TAV

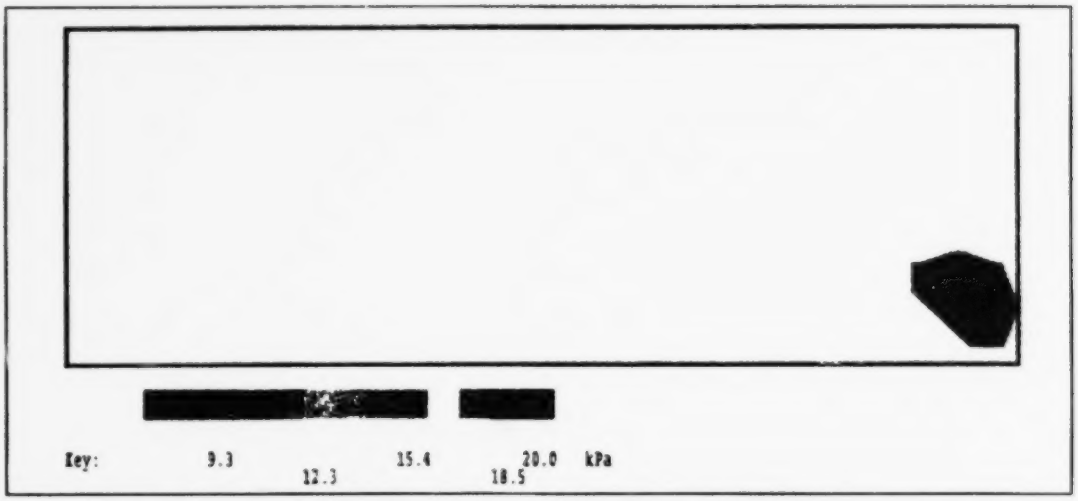
The following sections provide a more detailed breakdown of the pressure response in each anatomical area for testing of the CTS-FD rucksack, (no TAV).



**Anterior Shoulder**

The higher contact pressure occurs near the point indicated by the tip of the arrow. Pressures were low and within recommended ranges for extended wear.

Figure 3.2-1. Pressure map for anterior shoulder.




**Posterior Shoulder**

There was no significant contact in this area.

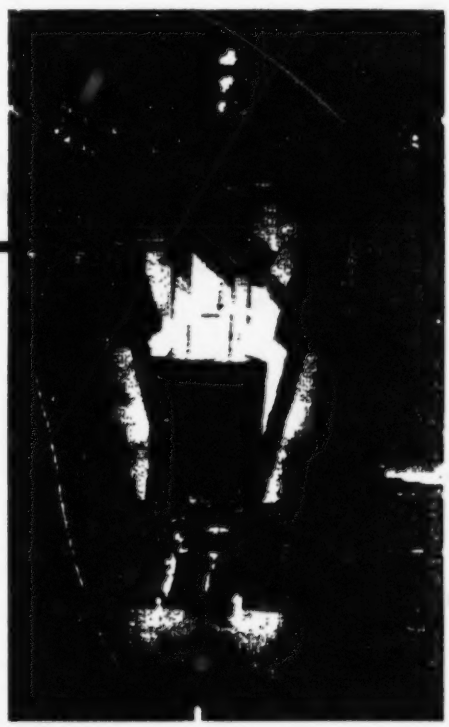
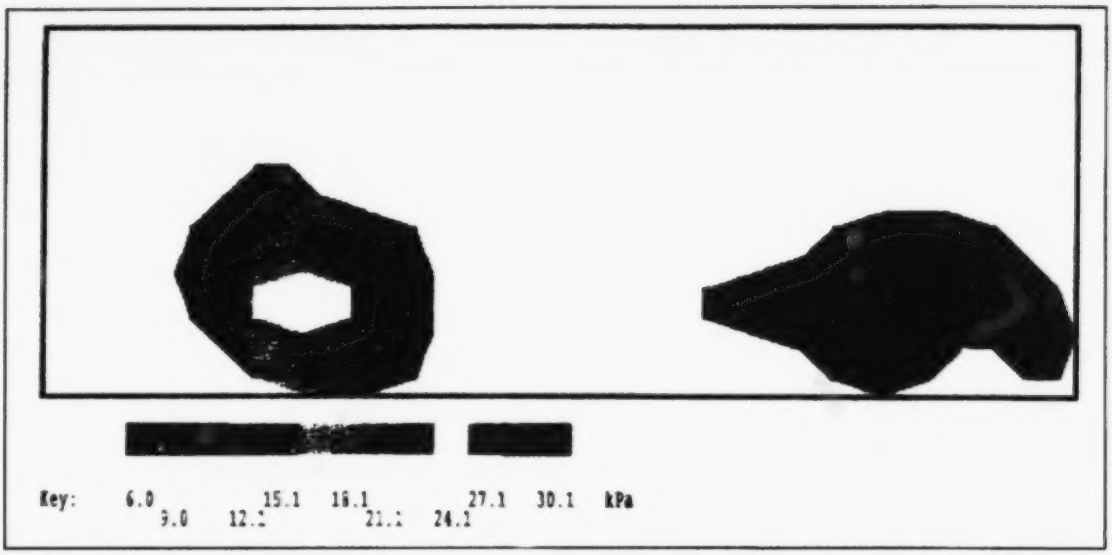


Figure 3.2-2. Pressure map for posterior shoulder, upper mid back

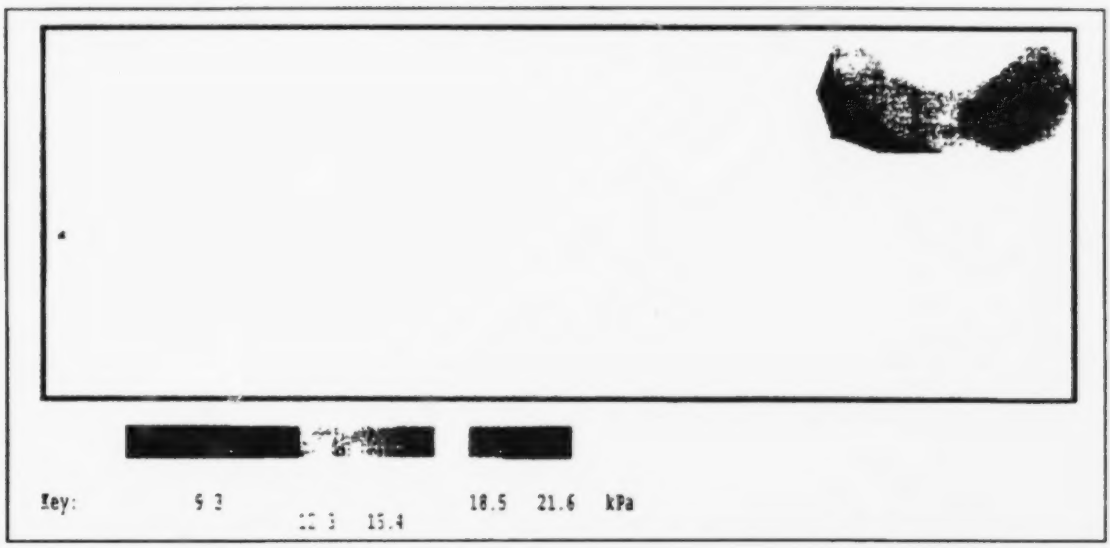



Contact pressures were within the recommended guidelines for continuous pressure.

**Note**: There was no significant pressure in the upper lumbar region.

**Lower Lumbar / Sacrum**

Figure 3.2-3. Pressure map for the lower lumbar / sacral region.




The contact occurring in the upper right corner of this plot was caused by the edge of the waist belt padding lying on the iliac crest. This result suggests that proper fitting of the waist belt includes positioning hip padding so that the edge does not lie directly above the bony landmark on the iliac crest.

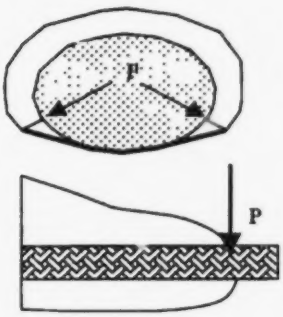
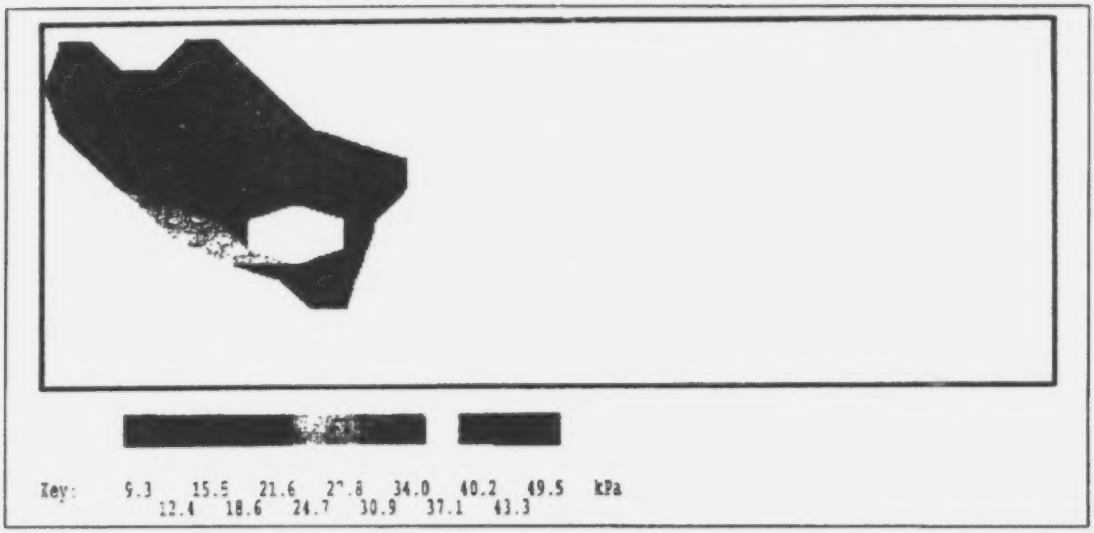


Figure 3.2-4. Pressure map for iliac crest and hip region.



The peak pressure (approximately 45 kPa) indicated on the contour plot occurred at the location indicated by the arrow tip. As the shoulder pad and strap wrap around the body, this area acts as a fulcrum and consequently experiences higher pressures.

**Axilla**

Figure 3.2-5. Pressure map of the axilla region

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The force-deflection diagrams of the pack for torsion, forward and sideways bending are shown in Figures 3.3-1, 3.3-2 and 3.3-3 respectively.

**Table 3.3-1** Stiffness values for the FD - CTS Rucksack, no TAV, system.

| | Torisonal Bending | Forward Bending | Lateral Bending |
|---|---|---|---|

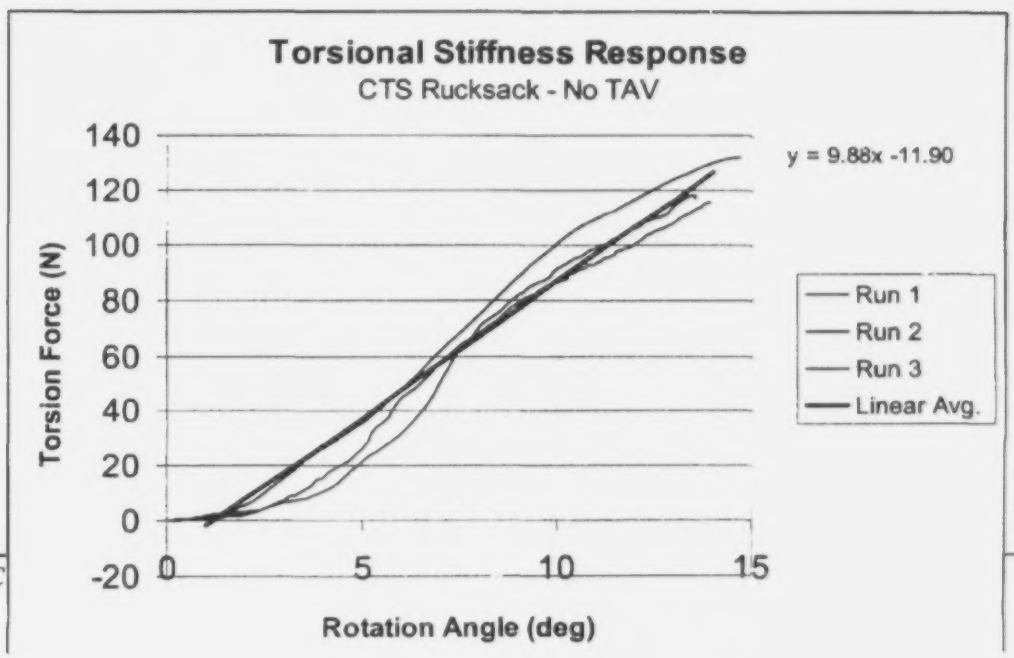

Figure 3.3-1. Twisting torque as a function of angle.
Torsional stiffness is defined as the average slope of the three test runs over the range of 1 to 14 degrees. Moment arm is 0.139 m.

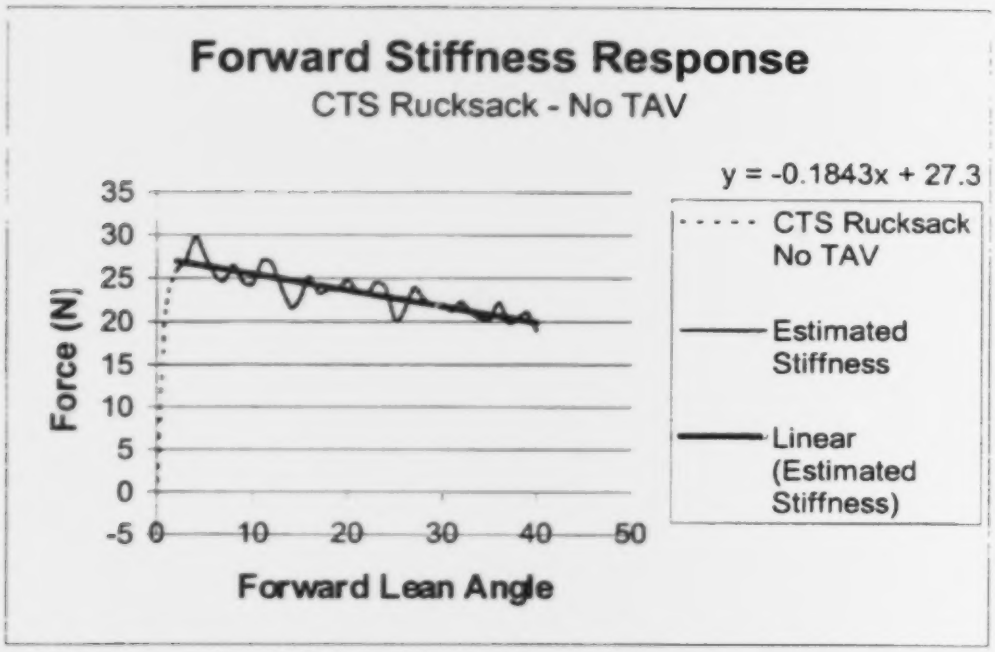


Figure 3.3-2. Forward bending force as a function of angle.
Forward bending stiffness is defined as the maximum slope of the graph. Moment arm is 0.927 m.

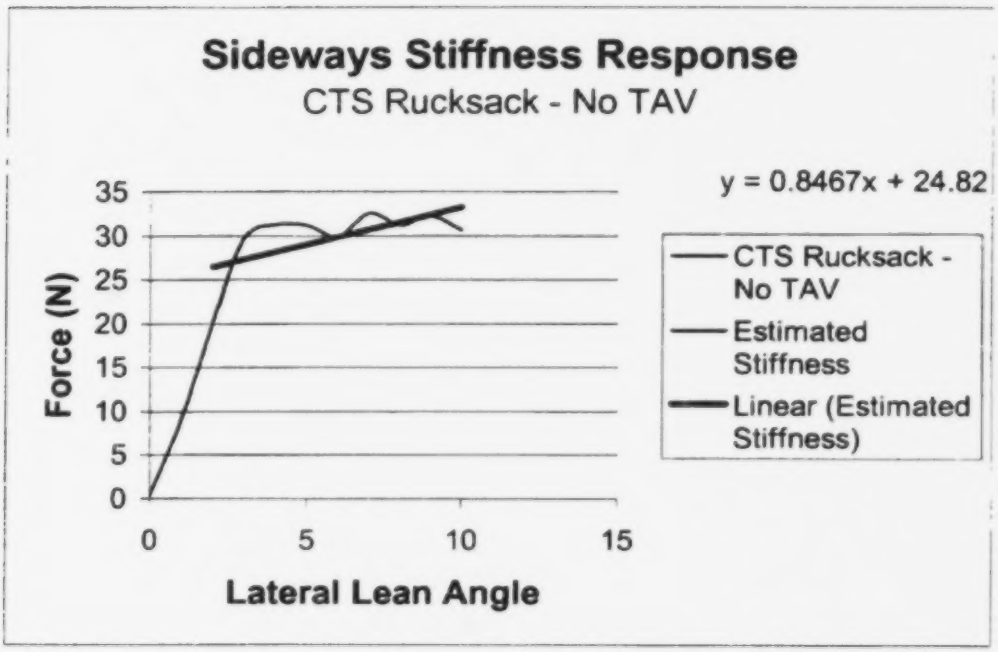


Figure 3.3-3. Lateral bending force as a function of angle.
Lateral bending stiffness is defined as the slope of the graph over the range of 2 to 11 degrees. Moment arm is 0.927 m.

# 4.0 Discussion

## *4.1 Comparison to Pressure Threshold Limit Values*

### 4.1.1 Average Contact Pressures.

As yet, no consensus exists regarding an acceptable safe limit for average skin contact pressures at the shoulder, lower back or hip. A maximum value of 14 kPa is currently recommended for exposures which exceed 8 hours in order to prevent skin necrosis due to blood occlusion [5]. Previous studies by this laboratory have indicated that average contact pressures at the shoulder which exceed 20 kPa will lead to discomfort in the neck and shoulder region in 95% of soldiers. This value is recommended as a threshold limit value for typical load carriage applications.

The CTS- FD Rucksack tested exhibited average pressures which were consistently less than 20 kPa with the exception of the axilla region, where average pressure was 24.1 kPa. Average pressures which exceed 20 kPa are typically found with military load carriage systems, and are likely to lead to discomfort in the region in which these pressures are experienced.

### 4.1.2 Peak Contact Pressures

The sensitivity of skin to instantaneous peak pressures varies widely with the nature of the pressure waveform and the region of the body under consideration. A value of 120 kPa is considered to be a conservative threshold limit value for peak pressures in the region of the shoulder, hip and waist.

In no case did the CTS – FD rucksack exhibit peak contact pressures which exceeded the threshold limit. The highest value observed, 46.4 kPa, was in the axilla region and contributed to the high average pressure (24 kPa) in this area. However, this area is vulnerable to injury because of the presence of the brachial artery and brachial plexus, which provides vascularization and innervation of the arm. The sternum strap should be used to position the shoulder straps medially, away from the immediate vicinity of these structures. Reducing the shoulder strap tension will also reduce pressure in this area.

## *4.2 Comparison to Current Benchmarks*

A statistical approach was developed under a previous study to compare the performance

[5]Holloway, JA., Daly, CH., Kennedy, D., and J. Chimoskey. (1976). Effects of external pressure loading on human skin blood flow. . *Journal of Applied Physiology* **40**: 596-600.

of load carriage systems. The method is based on two steps. In the first, a series of nine load carriage systems were evaluated using the LC simulator and the stiffness tester. The same systems were also evaluated in human factor trials. The correlation between physical measurements and human factor measurements indicated the objective values which significantly related to soldier load carriage performance acceptability. In the second step, the benchmark pool was examined to determine the spread of data within any physical measure among the nine packs. The appropriate means and standard deviations were used to establish confidence intervals. In this study, upper and lower deciles ($\alpha = 0.1$) were calculated. Thus, a load carriage system with a measured value outside this confidence interval has a likelihood of less than 10% of having performance equivalent to all members of the benchmark pool. Combining the two steps leads to consideration of the distribution of variables significantly correlated to human factors measures. In this way, the performance of any load carriage system can be meaningfully compared to several systems simultaneously. It also follows that the choice of systems included in the benchmark pool is critical, since an objective is to design a superior device.

### 4.2.1 Current Benchmark Pool

The current reference data are extracted from a previous study of currently available military load carriage systems. In this particular pool of nine systems, a number of ruck, webbing and vest permutations were examined. The systems were:

Australian Field Pack Large 1994 with webbing.
British UK-90 Pack and webbing.
DACME Packboard with Canadian 1982 webbing.
DACME Packboard with load carriage vest.
DACME Packboard with Canadian 1982 webbing and fragmentation vest.
DACME Packboard with load carriage vest and fragmentation vest.
Canadian 1982 issue with webbing.
Canadian 1982 issue with load carriage vest.
Canadian 1982 issue with webbing and fragmentation vest.

### 4.2.2 Comparison Variables

Significant correlations between measurements obtained from the LC simulator and stiffness tester and human factor measurements are indicated in Table 4.2-1. In total, 21 of 39 measures had significant correlation's with $p<.05$, including a number of variables which correlated with more than one human factor measure.

***Correlated LC Simulator and Human Factors Variables***
***Displacements and Forces***

| *LC Simulator Measures* | | | *Correlated Human Factors Measures* |
|---|---|---|---|
| *Displacement (mm)* | x | * | Posterior Hip Discomfort |
| | y | | |
| | z | * | Posterior Hip Discomfort |
| | r | * | Posterior Hip Discomfort |
| *Moment (Avg, Nm/kg)* | x (-ve) | | |
| | y (-ve) | * | Forward Flexion Mobility, Overall comfort, Overall Fit |
| | z | | |
| | r | | |
| *Force (Avg, N/kg)* | x | | |
| | y (-ve) | * | Front Mobility, Overhead Mobility, Posterior Shoulder Discomfort, March Thermal Comfort |
| | z | * | Front Mobility, Overhead Mobility, March Thermal Comfort |
| | r | | |
| *Moment (Amp, Nm/kg)* | x | * | Torsional Mobility, Overhead Mobility, Lie Function, Balance, Agility, Anterior Shoulder Discomfort, March Acceptability, March Comfort |
| | y | | |
| | z | * | Front Mobility |
| | r | * | Posterior Neck Discomfort |
| *Force (Amp, N/kg)* | x | | |
| | y | | |
| | z | * | Lie Function, Load Control, March Acceptability, March Integration, Overall Balance, Overall Comfort, Overall Maneuverability |
| | r | * | Load Control, March Integration |

**Table 4.2-1** Comparison variables.
Asterisk indicates LC system measures which are significantly correlated to human factors measures.

***Correlated LC Simulator and Human Factors Variables***
***Pressures and Stiffness***

| *LC Simulator Measures* | | | *Correlated Human Factors Measures* |
|---|---|---|---|
| *Shoulder Pressure (ANT)* | Av (kPa) | * | Posterior Hip Discomfort |
| | Pk (kPa) | * | Doffing Function |
| | PDI | * | Doffing Function |
| | F (N) | * | Posterior Neck Discomfort |
| *Shoulder Pressure (POST)* | Av (kPa) | | |
| | Pk (kPa) | * | Doffing Function |
| | PDI | | |
| | F (N) | | |
| *Lumbar Pressure (UPPER)* | Av (kPa) | | |
| | Pk (kPa) | | |
| | PDI | | |
| | F (N) | * | Posterior Discomfort |
| *Lumbar Pressure (LOWER)* | Av (kPa) | | |
| | Pk (kPa) | | |
| | PDI | * | Front Mobility, Posterior Discomfort |
| | F (N) | | |
| *Stiffness (Nm/deg)* | Torsion | * | Overhead Mobility, Front Mobility |
| | Flexion | * | Combined Function, Posterior Neck Discomfort, Low Back Discomfort |
| | Side | * | Front Mobility, Anterior Shoulder Discomfort, Anterior Hip Discomfort |

**Table 4.2-1 (continued).** Comparison variables. Asterisk indicates LC system measures which are significantly correlated to human factors measures.

### 4.2.3 Benchmark Comparisons

The comparison of test results to the current benchmark pool is shown in Table 4.2-2. In the table, the low decile, mean, and high decile is indicated for each variable. Generally, a low value indicates superior performance, and a high value indicates inferior performance. Exceptions are those values which are normally negative. These are indicated and are treated as absolute values in the analysis. Certain low decile values are unrealistically negative due to the computation methods used. These are treated as zero values for the purposes of analyzing results.

Measurements for the test pack are highlighted. Those measurements falling within high and low decile values are unremarkable and indicate that this parameter is typical of the benchmark pool. Those measurements falling outside the confidence interval are significantly different from the performance of the reference systems and are thus indicating superior or inferior attributes of the test system.

The implication of these results are discussed in terms of design considerations for load control, load transfer, and other factors.

***CTS - FD, No TAV Results***

| | | PERFORMANCE RESULTS | | | |
|---|---|---|---|---|---|
| Correlated Variable | *Superior* | *Low Decile* | *Mean* | *High Decile* | *Inferior* |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| *Displacement (mm)* | x | * | **1.32** | *1.32* | **1.60** | *6.82* | | *12 33* | |
| | y | | **0.84** | *1.06* | | *3 83* | | *6 60* | |
| | z | * | **0.52** | *7 47* | | *11 32* | | *15 17* | |
| | r | * | **1.65** | *8 16* | **9.40** | *14 06* | | *19 97* | |
| *Moment (Avg, Nm/kg)* | x (-ve) | | **0.50** | *0 07* | | *-0.07* | | *-0.21* | |
| | y (-ve) | * | **0.10** | *-0.13* | | *-0.26* | | *-0 39* | |
| | z | | **-0.03** | *0 01* | | *0 07* | | *0 14* | |
| | r | | | *0 16* | | *0.30* | | *0 43* | **0.50** |
| *Force (Avg, N/kg)* | x | | | *7.06* | **8.70** | *8.72* | | *10.37* | |
| | y (-ve) | * | **2.80** | *-1.06* | | *-1.25* | | *-1 44* | |
| | z | * | | *8 85* | | *8 94* | | *9 03* | **12.00** |
| | r | | | *11 49* | | *12.58* | | *13 66* | **15.10** |
| *Moment (Amp, Nm/kg)* | x | * | | *-0.01* | | *0.06* | | *0 13* | **0.40** |
| | y | | | *0 07* | | *0.32* | | *0 57* | **1.40** |
| | z | * | | *-0 01* | | *0.09* | **0.10** | *0 17* | |
| | r | * | | *0 11* | | *0.35* | | *0 59* | **1.50** |
| *Force (Amp, N/kg)* | x | | | *1 40* | **2.10** | *3.18* | | *4 96* | |
| | y | | | *-0 19* | | *0.05* | | *0 29* | **0.76** |
| | z | * | | *5 41* | | *7 32* | **8.04** | *9.22* | |
| | r | * | | *5.91* | | *8.05* | **8.30** | *10.18* | |

**Table 4.2-2** Comparison of LC system measures to current bench mark pool.
The low decile, mean, and high decile for each variable is shown. Measures which lie outside this range are either superior or inferior in comparison to the systems comprising the benchmark pool.

***Benchmark Comparison***
***Pressures and Stiffness***

*PERFORMANCE RESULTS*

| Correlated Variable | *Superior* | *Low Decile* | *Mean* | *High Decile* | *Inferior* |
|---|---|---|---|---|---|

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| *Shoulder Pressure (ANT)* | Av (kPa) | * | **15.40** | *21.78* | | *28.00* | | *34.22* | |
| | Pk (kPa) | * | **25.80** | *41.87* | | *72.26* | | *102.66* | |
| | PDI | * | | *1.63* | **1.67** | *2.57* | | *3.52* | |
| | F (N) | * | | *43.38* | **74.80** | *100.50* | | *157.62* | |
| *Shoulder Pressure (POST)* | Av (kPa) | | **6.20** | *13.63* | | *18.94* | | *24.26* | |
| | Pk (kPa) | * | **7.70** | *27.01* | | *49.71* | | *72.41* | |
| | PDI | | **1.24** | *1.34* | | *2.68* | | *4.02* | |
| | F (N) | | **4.00** | *22.40* | | *73.64* | | *124.89* | |
| *Lumbar Pressure (UPPER)* | Av (kPa) | | **#** | *6.86* | | *22.57* | | *38.27* | |
| | Pk (kPa) | | **#** | *10.12* | | *55.01* | | *99.90* | |
| | PDI | | **#** | *1.42* | | *2.37* | | *3.32* | |
| | F (N) | * | **#** | *2.10* | | *22.96* | | *43.81* | |
| *Lumbar Pressure (LOWER)* | Av (kPa) | | | *4.65* | **15.20** | *30.29* | | *55.93* | |
| | Pk (kPa) | | | *-2.39* | **27.10** | *84.87* | | *172.12* | |
| | PDI | * | | *1.32* | **1.78** | *2.81* | | *4.29* | |
| | F (N) | | | *-10.51* | | *56.52* | **58.30** | *123.56* | |
| *Stiffness (Nm/deg)* | Torsion | * | | *0.78* | | *2.13* | | *3.48* | **71.00** |
| | Flexion | * | **-0.20** | *0.11* | | *0.28* | | *0.44* | |
| | Side | * | | *-1.90* | **0.91** | *6.18* | | *14.18* | |

**Table 4.2-2 (continued).** Comparison of LC system measures to current bench mark pool. The low decile, mean, and high decile for each variable is shown. Measures which lie outside this range are either superior or inferior in comparison to the systems comprising the benchmark pool.

## *4.3 Design Considerations*

### 4.3.1 Load Control

*Displacement Effects*

The amount of relative displacement between a load and the users body that a LCS suspension system allows, bears directly on the users ability to control the load. Optimally, a load will closely follow the motion of the shoulders while allowing the hips to function with minimal resistance. Following the motion of the shoulders is particularly important during motions requiring large displacements (bending over, ducking under obstacles) or rapid changes in direction. Any large shifting of a heavy load in any direction, quickly becomes difficult for a wearer to restrain. This requirement leads to an upper boundary for the allowable relative displacement of a payload.

In contrast, low amplitude motions such as walking over level ground, require different suspension system characteristics. With small displacements and accelerations, the human body is able to easily balance slight shifts in the relative position of the load. In overly stiff suspension systems, the relatively small displacements of the body are still closely tracked, resulting in unnecessary forces on the body. All the accelerations and decelerations of the load will be directly transmitted to a users body. These forces, although not large, are cyclically applied and very long duration. As a result, they contribute to local muscle fatigue and higher peak contact pressures. This situation leads to a lower boundary for the allowable relative displacement of a payload. LCS suspension systems that restrain a payload more than is necessary, may pay a penalty in user comfort. The CTS-FD rucksack showed very good control over the relative displacement of the load. It was a superior performer in its control of anterior/posterior and vertical motions. Good displacement control is correlated with reduced posterior hip discomfort.

*Stiffness Effects*

The resistance that a LCS offers to motion is related to the human effort required to force that LCS into the required geometry. A trade-off occurs between the small amplitude motions of gait and the large motions required for manoeuvrability. In large magnitude motions, high bending and torsional stiffness work against the user. The user must assume awkward or less stable postures to achieve the range of motion required, thus decreasing their ability to control their load. For small amplitude motions like gait, the stiffness of a LCS may allow it to transfer load effectively to the skeleton and if the range of motion required for gait is not restricted, it will perform well during walking. Therefore, for optimal load control, the combined design elements that provide stiffness to a LCS should constrain the load without constraining a user.

The CTS-FD rucksack showed typical stiffness characteristics in sideways bending. It showed superior stiffness characteristics in forward flexion. Low stiffness in flexion has been shown to be correlated to good combined functional ratings where large movements are required, reduced posterior neck discomfort and reduced low back discomfort. The high torsional stiffness of the CTS-FD rucksack will result in an inferior performance in overhead mobility (reaching above the head) and front mobility (reaching forward) tasks. The location of the lateral stiffing rods on the outside of the frame sheet and hips effectively gives a large moment arm and maximizes the rods effect on torsional stiffness. Since the user can release these rods at will, this effect can be controlled and torsional stiffness is user controllable.

### 4.3.2 Load Transfer

There are several factors limiting an individual's ability to carry load. These are: local muscle fatigue caused by unrelieved muscle contraction, transverse shear load through the spine,

local contact pressure resulting in the compression of nerves, point pressures on underlying structures, and high continuous contact pressures causing compression of underlying tissue and a subsequent inability to oxygenate the tissue.

*Forces and moments*

The stiffness elements within a LCS design and the suspension system should serve to transmit the vertical load through the skeleton and onto the spinal column. Any transverse shear load on the spine that is induced by the design is parasitic and can quickly become the limiting factor in load carriage ability. Typically the shoulder girdle and the pelvis are used as the main load transfer sites and are particularly suited for load control and transfer. The average magnitude of the hip reaction force is a direct indicator of the muscle force required by an individual to support this load and LCS. The amplitude of the reaction forces reflect the ability of a LCS suspension system to attenuate the dynamic loading. High amplitudes will require additional muscle forces for load control and a LCS demonstrating high reaction force amplitudes will typically be more energy costly to wear.

The tight control of the displacement of the payload that the CTS-FD demonstrated results from a "stiff" suspension system. This typically results in higher reaction forces and moments due to the acceleration changes required to achieve this motion control. The CTS-FD rucksack was a inferior performer with high average vertical reaction forces. It demonstrated typical performance in the anterior/posterior and superior medial/lateral mean reaction forces at the hip. High vertical reaction forces have been correlated with decreased front mobility, decreased overhead mobility and increased marching thermal discomfort.

This LCS also showed typical vertical and resultant force amplitude characteristics. These factors are correlated to good load control, march acceptability and overall good balance performance.

*Average pressures*

The average contact pressure in a load transferal region reflects how successful a design is in using the contact site while minimizing the risk of causing tissue damage. Tissue damage may result from continuous compression of underlying tissue and the subsequent inability of the body to oxygenate the tissue Studies[6] indicate that a safe physiological limit for continuous pressure over 8 hours is 14 kPa, the contact pressure threshold limit for the perception of pain is 20 kPa[7]

The CTS-FD rucksack showed superior anterior shoulder strap performance with an average contact pressure of 15.4 kPa in the anterior shoulder region and less than 10 kPa in the posterior shoulder region. Low pressures in these areas reduce the incidence of posterior hip discomfort, improves doffing function and reduces posterior neck discomfort.

Average contact pressures in the lower lumbar / sacrum sites were typical at 15.2 kPa which is approaching the guidelines for long term (8 hour) exposure.

*Peak pressures*

Large peak pressures reflect pressure concentrations that can lead to bruising or cause tissue damage due to the inability to oxygenate the tissue. Studies have indicated that the tissue tolerance limit for short duration contact pressure (less than 5 minute) is in the order of 120 kPa.

The CTS showed a superior pressure distribution at the anterior and posterior shoulder with very low peak pressures. Low peak shoulder pressures are related to ease of doffing a LCS. The peak and average pressures in the upper lumbar area are typical and result in a transverse load of 58 N. Although high transverse shear loads are associated with high posterior discomfort in users, this value is well below the threshold limit value of 135N for transverse loads on the spine based on achieving optimal human load carriage performance, as determined in a previous study[8].

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[6]Stevenson, JM., Bryant, JT., Pelot, RP , Morin, EM., Deakin JM., Reid, SA., Doan, JB., (1997) Research and Development of an Advanced Personal Load Carriage System, Phases II and III, DCIEM Contract # W7711-5-7273/001/TOS.

[7]Holloway, JA., Daly, CH , Kennedy, D . and Chimoskey. (1976) Effects of External Pressure Loading on Human Skin Blood Flow. Journal of Applied Physiology **40**: 596-600.

[8]Stevenson, JM., Bryant, JT , Reid, SA., Doan, JB., et al. (1995) Research and Development of an Advanced Personal Load Carriage System, Phases I. DCIEM Contract # W7711-4-7225/01-XSE.

# 5.0 Conclusions and Recommendations

## *5.1 Conclusions*

1. The CTS rucksack was compatible with the standardized dynamic testing methods developed to assess military load carriage systems, subject to the reservations noted.

2. Compared to a benchmark pool of nine military load carriage systems testing of the CTS-FD pack indicated superior performance in:

    - Control of relative pack-torso motion,
    - Low average and peak pressures in the anterior and posterior shoulder region, and
    - Lower average reaction moments for vertical, medial/lateral and forward reaction moments at the hip.

3. Compared to a benchmark pool of nine military load carriage systems testing of the CTS-FD ruck indicated inferior performance for correlated variables in:

    - Higher vertical reaction forces at the hip,
    - Higher anterior/posterior moment amplitudes at the hip, and
    - Higher torsional stiffness when stiffening rods are tensioned. Tension in the rods is user controllable.
    - Although the average contact pressure in the axilla is in the acceptable range, the peak pressure value of 45 kPa may be of concern due to the proximity to the brachial artery and brachial plexus.

4. The transverse force in the lumbar region is below the value expected to cause discomfort in this area.

## *5.2 Recommendations*

1. The long term effects of torsional stiffness on energy cost and user comfort should be studied.

# 6.0 Reservations

Although testing of a military rucksack in the absence of battle order is of limited value in the prediction of performance under field conditions, it is useful in determining the effect of

the webbing (or load carriage vest) on the performance of the pack. Quantifying negative changes in the response of the suspension system, pressure distribution or stiffness characteristics can help determine exactly what interaction of equipment is responsible. This information will inform designers and users about the root cause of the degradation in field performance.

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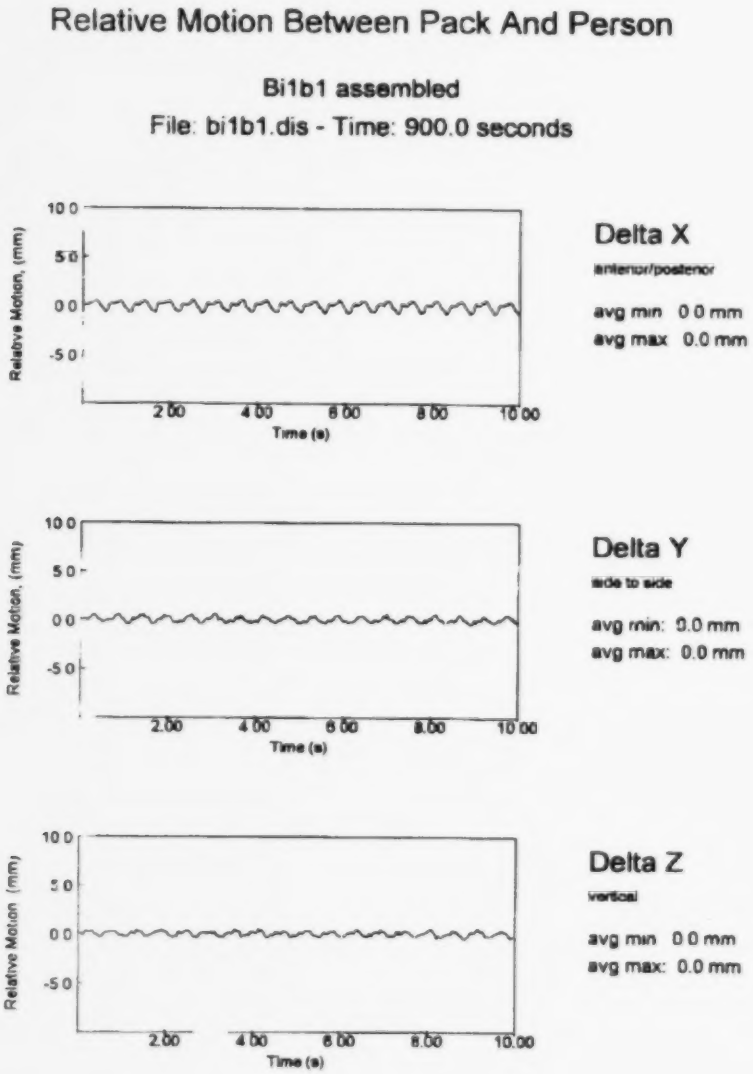
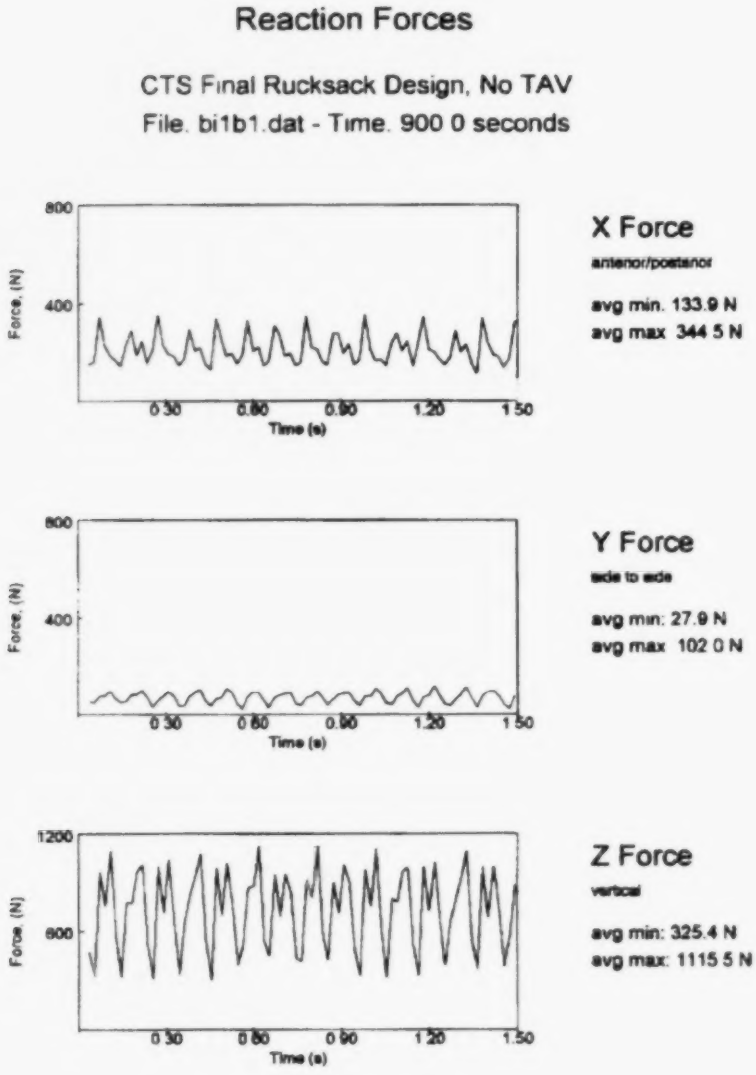
**Annex 3.1**

*3.1 Test Results for CTS – FD, No TAV*

3.1.1 Relative Pack-torso Displacement over Ten Seconds.
3.1.2 Reaction Forces over Ten Seconds.
3.1.3 Reaction Moment over Ten Seconds.
3.1.4 Strap Forces over Ten Seconds.



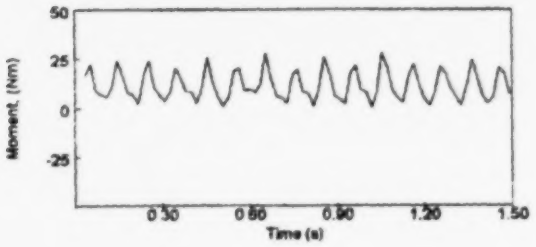

Annex 3.1.1 Relative Pack-torso Displacement over Ten Seconds.




Annex 3.1.2 Reaction Forces over Ten Seconds.

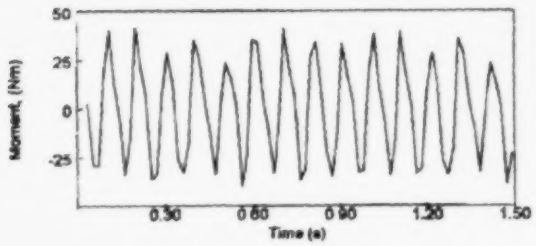
## Reaction Moments

CTS Final Rucksack Design, No TAV
File: bi1b1.dat - Time. 900.0 seconds



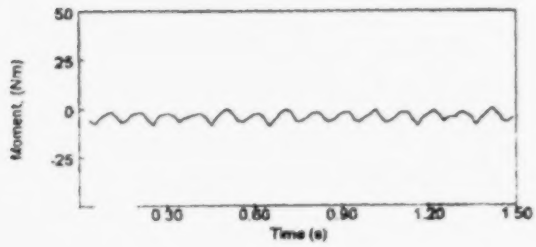

**X Moment**
about anterior/posterior axis

avg min 1.2 Nm
avg max 26.3 Nm




**Y Moment**
about side to side axis

avg min. -37.1 Nm
avg max. 39.2 Nm




**Z Moment**
about vertical axis

avg min: -8.3 Nm
avg max: -0.2 Nm

3.1.3 Reaction Moment over Ten Seconds.

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**4. AUTHORS**

S.A. Reid J.M. Stevenson E.L. Morin J.T. Bryant

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14. ABSTRACT

(U) The objective of this study was to conduct a standardized assessment of the Clothe the Soldier Integrated LCS pack, Final Design (CTS-FD) on a computerized Load Carriage (LC) Simulator. Specifically, the LC Simulator measured variables which assess the load control and load transfer capability of the CTS Integrated LCS pack. These aspects of pack design were comprised of several displacement, force, moment and pressure variables that had been validated on previously tested systems where LC Simulator outputs were compared to assessments by experienced users during human trials. The CTS-FD pack was evaluated without the Clothe the Soldier tactical assault vest (TAV).
The LC Simulator consisted of interchangeable anthropometrically weighted manikins (50th percentile male used) which were covered with a skin-like surface, driven by computer controlled pneumatic activators programmed to elicit a walking displacement pattern of +25.4 mm amplitude and 1.8 Hz frequency. A trial consisted of measuring inertial properties and dimensions, loading the pack with a 25 kg payload, mounting the pack and balancing the moments. Five intervals of 10 seconds of data were recorded over a 1200 second period. By this approach, the pack was assessed on the initial setup and after a sustained period of walking. Output variables were: three dimensional motions of the pack's centre of gravity relative to the person's motion; forces and moments from a three dimensional load cell at the level of the hips; skin average pressures, peak pressures and skin forces over the anterior and posterior shoulders, and upper and lower back.
To examine the resistance of the pack frame to motions in three planes, a pack stiffness jig was developed. This jig consisted of a two-piece anatomical human trunk model (50th percentile male) which was designed to confine motion to one plane at a time. Using a load cell and multi-turn precision potentiometer, pack resistance to flexion/extension, lateral bending and torsion were evaluated through a set protocol.
The CTS-FD rucksack performance was compared to previously validated variables for load control and load balance from the LC Simulator. Results were expressed in comparison to the mean value, superior decile (best 10%) and inferior decile (worst 10%) values. For load control, the CTS-FD rucksack ranked as superior on: control of relative pack-torso motion, lower average and peak pressures in the anterior and posterior shoulder region, and lower average reaction moments for vertical, medial/lateral and forward reaction moments at the hip.

15. KEYWORDS, DESCRIPTORS or IDENTIFIERS

(U)